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Development of a simulation environment for ground control laws design

Thiago Giusti Degaspare
Pedro Paglione
Instituto Tecnológico de Aeronáutica, Divisão de Engenharia Aeronáutica, Departamento de Mecânica do Vôo. Praça Mal. Eduardo Gomes, 50. Vila das Acácias. Sao Jose dos Campos, SP - Brazil
thiago.degaspare@embraer.com.br,paglione@ita.br

Cleverson Maranhão Porto Marinho
Embraer. Avenida Brigadeiro Faria Lima, 2170. São José dos Campos, SP - Brazil
cleverson.marinho@embraer.com.br

Abstract. *Flight controls systems based on fly-by-wire technology are a common practice in the modern aeronautical industry. Their advantages are associated with pilot load work reduction, handling qualities improvements, structural loads optimization and envelope protection, during different flight phases. A common use of on-ground control law is tail-strike protection, in which pitch attitude is limited in order to avoid a tail strike during takeoff rotation. However, few studies in the literature are dedicated to the influence of on-ground dynamics on the aircraft behavior and control law design. This work aims to explore this gap by the development and study of an aircraft model contemplating not only aerodynamic aspects but also on-ground dynamics, achieving a better understanding of its influence on the aircraft behavior and driving requirements that serve as inputs for control laws design. The model is based on a low wing twin jet engine high performance aircraft. A study is proposed, in which the nonlinear model is used for trimming the aircraft in different phases during takeoff and linear models are derived for aircraft rotation. These are used to understand the influence of on-ground dynamics in terms of stability and control of the aircraft. This practice allows to address characteristics introduced by the highly non-linear on-ground dynamics that otherwise would be neglected, thus improving results on control law design.*
Keywords: *simulation, on-ground dynamics, aircraft trim, fly-by-wire, stability and control*

1. VARIABLES AND DEFINITIONS

p	Roll rate	L_b	External moment component (body x-axis)
q	Pitch rate	M_b	External moment component (body y-axis)
r	Yaw rate	N_b	External moment component (body z-axis)
x_e	x-position (earth x-axis)	α	Angle-of-attack
y_e	y-position (earth y-axis)	C_L	Lift coefficient
z_e	z-position (earth z-axis)	π_b	Brake input
ϕ	Euler angle	π_e	Engine input
θ	Euler angle	δ_e	Elevator input
ψ	Euler angle	δ_{ih}	Horizontal stabilizer input
u_b	Velocity component (body x-axis)	δ_a	Aileron input
v_b	Velocity component (body y-axis)	δ_r	Rudder input
w_b	Velocity component (body z-axis)	ϵ	Downwash angle
X_{sp}	External forces component (body x-axis)	rh	Right-handed
Y_{sp}	External forces component (body y-axis)	lh	Left-handed
Z_{sp}	External forces component (body z-axis)	ht	Horizontal tail
I_{ab}	Moment of inertia component		

2. INTRODUCTION

Most of the fly-by-wire design is driven by requirements that translate performance, handling qualities, safety and availability, among the most important ones. Control law techniques and architectures are very well developed in the literature for flight applications, such as stability or control augmentation systems and automatic pilots.

Even if flight phases may represent most of an aircraft typical mission, on ground phases are quite important as well, which is justified by safety reports delivered by aircraft manufacturers. A safety report from Airbus (2014), states that nearly 90% of the accidents happened during descent, approach and landing or takeoff and climb phases, even if they correspond to the shortest segments of a typical transport aircraft mission.

Fly-by-wire aircraft have indeed some envelope protections for on ground phases, such as tail-strike and high angle of attack protection. However, the literature in this field remains limited when compared to flight envelope protections. The main purpose of this work is to explore this gap by the development of an aircraft model that allows for fly-by-wire control law development during the takeoff phase.

In order to fully understand the aircraft dynamics on ground and allow for drivers that would lead to requirements for fly-by-wire control law design, it is necessary to have a model that represents adequately the aircraft on ground. It is important to balance its the complexity, once on ground dynamics are generally highly non-linear.

An aircraft model is developed taking into account ground efforts and ground effect. The aircraft consists of a twin-engine high swept wing jet. The model is used for analyzing the aircraft dynamics on ground and also in the determination of linear models obtained for different envelope configurations and operating points. This analysis is then extended in defining fly-by-wire requirements that drive control laws used in the design of stability augmentation systems, control augmentation systems and autopilots.

3. THE TAKE-OFF MANEUVER

All definitions and regulations concerning takeoff for transport category aircraft may be found at FAR Regulations 14 CFR 25. The takeoff maneuver is also described by Roskam and Lan (1997) and Roux (2005). In general, it can be divided into three phases: ground-roll, air distance and climb-out, as suggested in Fig. 1.

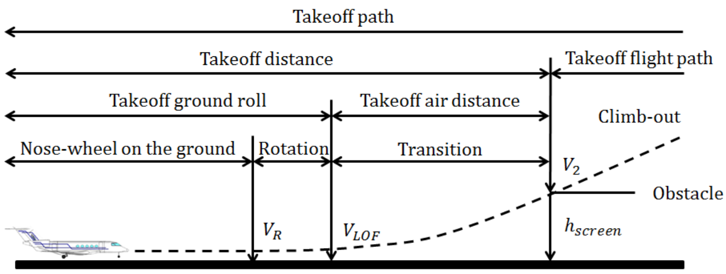


Figure 1: Take-off phase description

The takeoff ground roll considers an accelerated motion until V_R, which is defined as the rotation speed. Then, the aircraft is commanded nose up and climbs at speed V_{LOF}, lift-off speed. The flight path angle varies from zero to some value defined generally by performance requirements. From, V_{LOF} until V_2, the aircraft must reach a screen height, h_{screen}, which corresponds to the obstacle security height defined by aeronautical regulations.

4. AIRCRAFT MODELING

Figure 2 shows the main components of the airframe integrated model. Its overall construction is discussed below, with focus on effects that influence the aircraft behavior on ground, namely ground effect and ground efforts. Flight actuators and propulsive efforts will not be detailed. These are modeled with the use of simple first order transfer functions. The atmospheric model will not be detailed as well. It is adopted the *International Standard Atmosphere*.

The aircraft model is derived considering a flat-earth approximation. This is suitable for the purposes of low-speed flight simulation over a small region of the earth and with no requirements for precise simulation of position. The earth is assumed to be an inertial frame, once its accelerations are negligible compared to the ones which can be achieved by aircraft maneuvers. The different frames and coordinate systems used are the aircraft reference frame, referenced as body frame, and stability axes reference frame.

The complete set of the equations of motion is presented as in Eq. (1) to Eq. (12). For the purposes of this work, the main authors considered were Pamadi (1998), Stevens (2003) and Etkin (1959).

$$\dot{p} = \frac{I_{xz}\dot{r} + I_{xz}pq - (I_{zz} - I_{yy})rq + L_b^{ext}}{I_{xx}} \quad (1)$$

$$\dot{q} = \frac{-(I_{xx} - I_{zz})pr - I_{xz}(p^2 - r^2) + M_b^{ext}}{I_{yy}} \quad (2)$$

$$\dot{r} = \frac{I_{xz}\dot{p} - (I_{yy} - I_{xx})pq + N_b^{ext}}{I_{zz}} \quad (3)$$

$$\dot{x_e} = U\cos\theta\cos\psi + V(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) + W(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \quad (4)$$

$$\dot{y_e} = U\cos\theta\sin\psi + V(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) + W(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \quad (5)$$

$$\dot{z_e} = -U\sin\theta + V\sin\phi\cos\theta + W\cos\phi\cos\theta \quad (6)$$

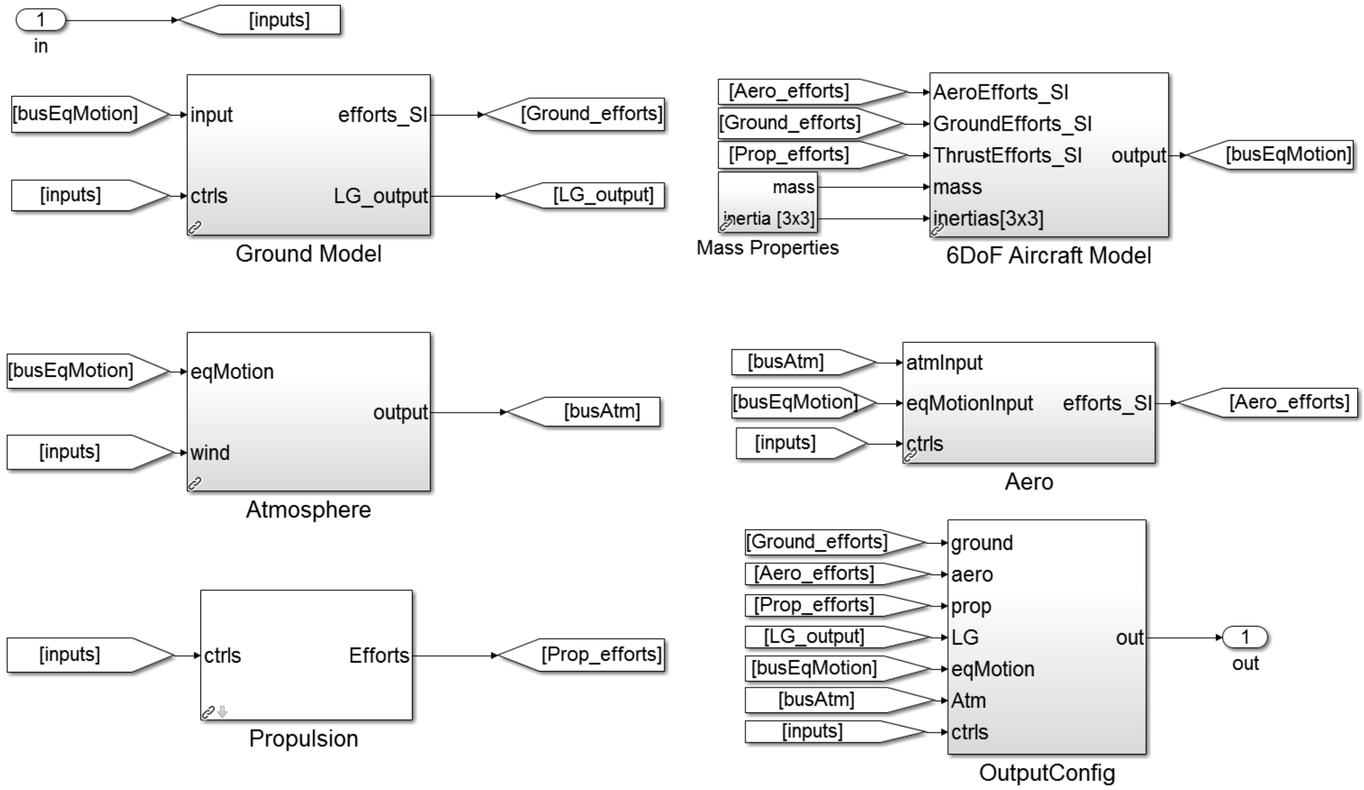


Figure 2: Overview of model main components

$$\dot{\phi} = p + \tan\theta(q\sin\phi + r\cos\phi) \quad (7)$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \quad (8)$$

$$\dot{\psi} = (q\sin\phi + r\cos\phi)/\cos\theta \quad (9)$$

$$\dot{u_b} = v_b r - w_b q - g\sin\theta + \vec{X_{sp}}/m \quad (10)$$

$$\dot{v_b} = w_b p - u_b r + g\sin\phi\cos\theta + \vec{Y_{sp}}/m \quad (11)$$

$$\dot{w_b} = u_b q - v_b p + g\cos\phi\cos\theta + \vec{Z_{sp}}/m \quad (12)$$

The aircraft model divides the external forces and moments into different categories, each of them modeled separately and them assembled together, as presented in Fig. 2.

4.1 Ground effect

Preliminary estimation of aerodynamic coefficients is possible through the use of linear relationships, obtained with the linearization of its complete expressions around a point of interest in the operational envelope. This is the approach used herein. A detailed discussion on the method of estimation and the meaning of each coefficient can be found in the works of Stevens (2003), Pamadi (1998) and Roskam (2000). The detailed modeling of aerodynamic coefficients is quite complex due to its dependence on several variables and non-linearities. Normally, this requires an extensive aerodynamic data bank and several wind-tunnel experiments. The model comprises a contribution from the wing-body ensemble and other contributions due to rotation rates and control surfaces such as aileron, elevator, rudder and horizontal stabilizer. An additional contribution considered is due to ground effect influence.

The ground effect is a phenomenon that occurs during certain flight phases such as takeoff and landing. The presence of the ground causes modifications that may have influence in trimming and stability. Etkin (1959) gives a brief description of this phenomenon. In general, the presence of the ground imposes a boundary condition that inhibits the downward flow of air normally associated with the lifting action of the wing and tail. The main effects are a reduction in the downwash angle at the tail, an increase in the wing-body lift slope and in the tail lift slope.

The implementation follows the procedures described by ESDU-72023 (2014). The method takes into account the lift and pitching moment curves with retracted and extended flaps. Generally, it combines a change in incidence, noted $\delta\alpha$ at a given lift coefficient with a change in lift coefficient δC_L at the new incidence.

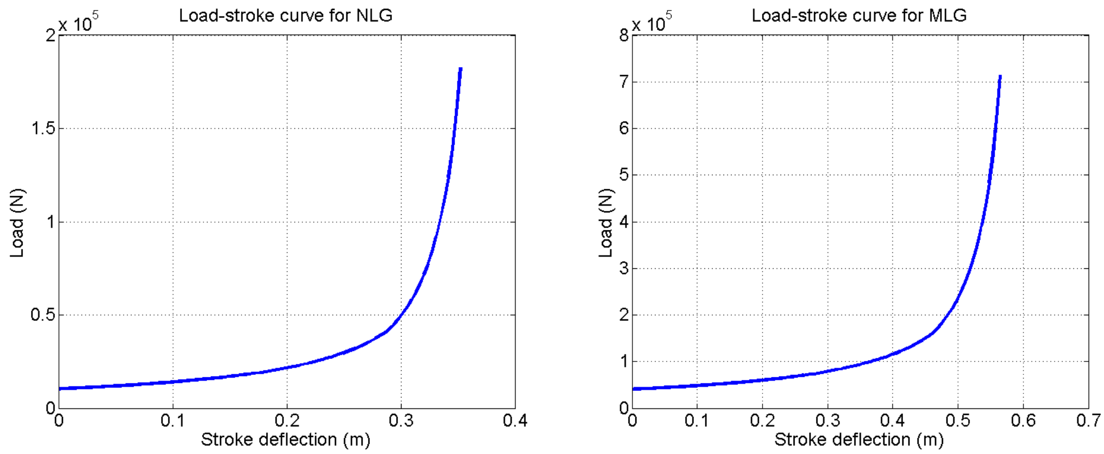
4.2 Ground efforts

The ground efforts derive most from landing gears and tires dynamics coupled with the aircraft. The model is based mostly on the works of Hanke *et al.* (1971). Currey (1988) describes methods and explains many aspects related to landing gear design. The final build up was compared and validated with the works of Turbuk (2009) and Kosoniscs (2010).

The landing gear system for the considered aircraft has a tricycle configuration with telescopic nose gear and trailing-arm main gears. Some simplifications are made with respect to this configuration: the main landing gears are considered as telescopic one. The contact point between the tires and the ground is preserved in its original position, however the trailing-arm effects are not taken into account.

The phenomena involved in landing gear modeling are quite complex and described by Pritchard (1999). Flexibility effect as well as shimmy vibration are not taken into account in this model, which considers a rigid-body approach, simplified for the purposes of this work. Other simplifications are related to tire models, which are subject to numerous non-linearities, as presented by Smith (2004) and Jones (2012).

Three main force components are modeled. Firstly, the oleo strut forces, which are due to compression or extension of shock absorbers. They are modeled according to method proposed by Currey (1988) and Hanke *et al.* (1971). They are primarily a function of stroke displacement and its rate. Examples of load-stroke curves obtained with these methods are presented in Fig. 3a and Fig. 3b.



(a) Load-stroke curve for NLG (b) Load-stroke curve for MLG

Figure 3: Load stroke curves for landing gears

Two other important components are the wheel side forces and the wheel drag forces. The former are due to friction in lateral direction and the wheel sideslip angle. The approach used adopts a simplified modeling, merging the works of Hanke *et al.* (1971), Kosoniscs (2010) and Turbuk (2009). The wheel drag forces take into account longitudinal friction forces originated both from the tire rolling movement and also brake actuation.

5. MODEL ANALYSIS

The model previously developed has the following state variables and inputs, according to Eq. (13):

$$\begin{aligned} X &= \begin{bmatrix} p & q & r & x_e & y_e & z_e & \phi & \theta & \psi & u_b & v_b & w_b \end{bmatrix}^T \\ U &= \begin{bmatrix} \pi_b^{lh} & \pi_b^{rh} & \delta_e & \delta_{ih} & \delta_a & \delta_r & \pi_e^{rh} & \pi_e^{lh} \end{bmatrix}^T \end{aligned} \tag{13}$$

5.1 On ground trimming

Few works in the literature give insight on how to trim the aircraft on ground. Generally, approximative approaches are adopted, such as to trim the aircraft model for a condition sufficiently near the ground but without tire contact. The main difficulties are related with the non-linearities introduced by ground effect and landing gear models.

The works developed by Pashilkar (1996) deals with this problem adopting a step-by-step trim for different takeoff phases until complete lift-off. Another example is Chudoba and Cook (2003), that considers a quasi-static equilibrium for all aircraft state variables at one point prior to complete lift-off.

The method adopted follows the main ideas of Pashilkar (1996). The examples are developed for the longitudinal case and would be also suitable for the lateral-directional case. Given the aircraft non-linear model, the longitudinal states and inputs, it is desired to find a trim point for three different situations: rotation on both wheels till nose wheel lift-off point, on ground roll with fixed attitude and in air roll.

The longitudinal state variables are defined as in Eq. (14).

$$X_{long} = \begin{bmatrix} u_b & w_b & q & \theta & z_e \end{bmatrix}^T \tag{14}$$

The aircraft is supposed at V_R, with fixed horizontal stabilizer deflection and full throttle inputs. As for inputs, the only variable considered for trimming purposes is the elevator deflection δ_e. Estimation of fixed quantities for on ground trim are given according to Eq. (15) and Eq. (16).

$$V_R = max\left(\frac{1.05}{1.1}V_2, 1.05V_{mc}\right) \tag{15}$$

$$\delta_{ih} = \alpha_{ht} - \alpha + \epsilon \tag{16}$$

The trim algorithm computes, from the complete non-linear model, a trim point specified by different constraints. These shall be defined by fixed or float conditions for each model input, output, state variable and the derivatives of state variables. Due to takeoff particularities, the constraints are defined such that u_b and w_b are the only floating longitudinal states. Nevertheless, the trim point is always computed around V_R, by defining the aircraft speed as a fixed output. Using the same approach, it is possible to monitor landing gear efforts and deflections for each trim point and use them as constraints as well. The main quantities of interest for longitudinal analysis are mainly the elevator deflection and aircraft attitude.

The trim points are obtained for the three situations described below. From them, it is possible to compute linear models that will be used in the analysis of on ground aircraft dynamics.

5.1.1 Rotation on both wheels till nose wheel lift-off point

This allows to compute a trim point for which the aircraft has just lifted the nose wheel off the ground, at speed V_R. The constraints imposed for the trim algorithm are such that the deflection of the nose landing gear is constant and equal to zero, i.e., it has just lifted-off the ground. The aircraft attitude is fixed to very small values, around $0.5\,\text{deg}$.

5.1.2 On ground roll with fixed attitude

The trim point is computed for a given fixed attitude, that would represent the initial rotation of the aircraft. The values are restricted in the interval of $[5, 10]\,\text{deg}$. The constraints imposed for the trim algorithm are such that the initial deflection of main landing gears is not zero, but there is not an explicit constraint fixing neither nose or main landing gear deflections. It is possible to obtain different trim points by varying the initial landing gear deflections, together with z_e and the attitude θ.

5.1.3 In air roll

This situation considers that the main landing gears have just lifted-off the ground, with the aircraft completely airborne, but still under the influence of ground effect, at a small altitude. It is not necessary to adopt any additional constraint regarding the landing gear deflection. In this case, the CG height is considered fixed at $5\ m$ above the ground.

5.2 Control and stability analysis

Figure 4 shows the aircraft CG and weight envelope used in the analysis. The conditions set for the determination of the trim points may be applied for several takeoff conditions within this envelope. The example presented considers the case of an aft CG position at MTOW, which corresponds to point 4. This is considered as a representative point for the analysis, which can be extended to other points as well.

Applying the trimming conditions for the three situations formerly described, it is possible to compute trim points and derive linear models for the aircraft longitudinal mode. The linear models are defined by using a first order Taylor series approximation computed around the trim point, as in Eq. (17).

$$\begin{cases} \Delta\dot{X} = A\,\Delta X + B\,\Delta U \\ y = C\,\Delta X + D\,\Delta U \end{cases} \tag{17}$$

where $\Delta X = X - X_{trim}$, $\Delta U = U - U_{trim}$ and the matrices A, B, C and D are obtained from the Taylor series first order approximations of the non-linear model written as a function X and U.

Then, given the full state linear model and the longitudinal state variables and inputs, the longitudinal linear model is decoupled according to 14. This is described as in Eq. (18).

$$\begin{aligned} \dot{X} &= A_{long}\,X_{long} + B_{long}\,U_{long} \\ y &= C_{long}\,X_{long} + D_{long}\,U_{long} \end{aligned} \tag{18}$$

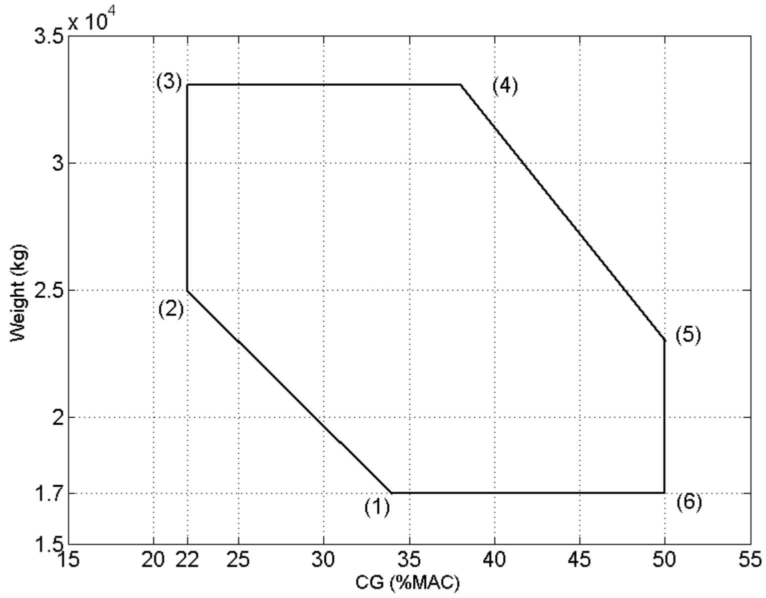


Figure 4: CG and weight envelope

The linear eigenvalues are computed directly from matrix A_{long}. Figure 5 shows the mapping of eigenvalues for the three trim points considered. For this particular CG and weight position, the trim points are defined as in Tab. 1.

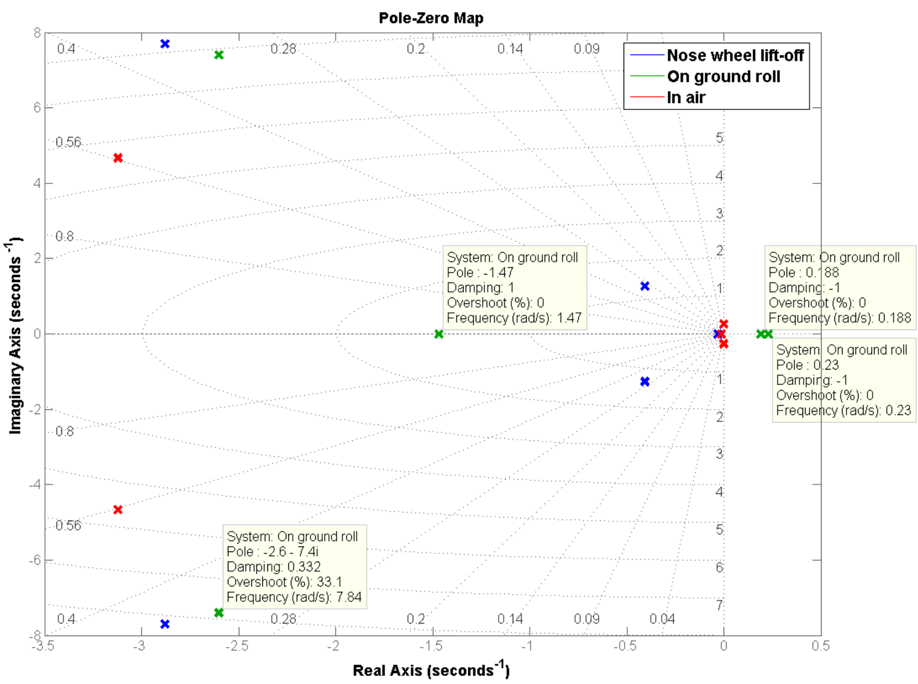


Figure 5: Eigenvalues for takeoff longitudinal modes

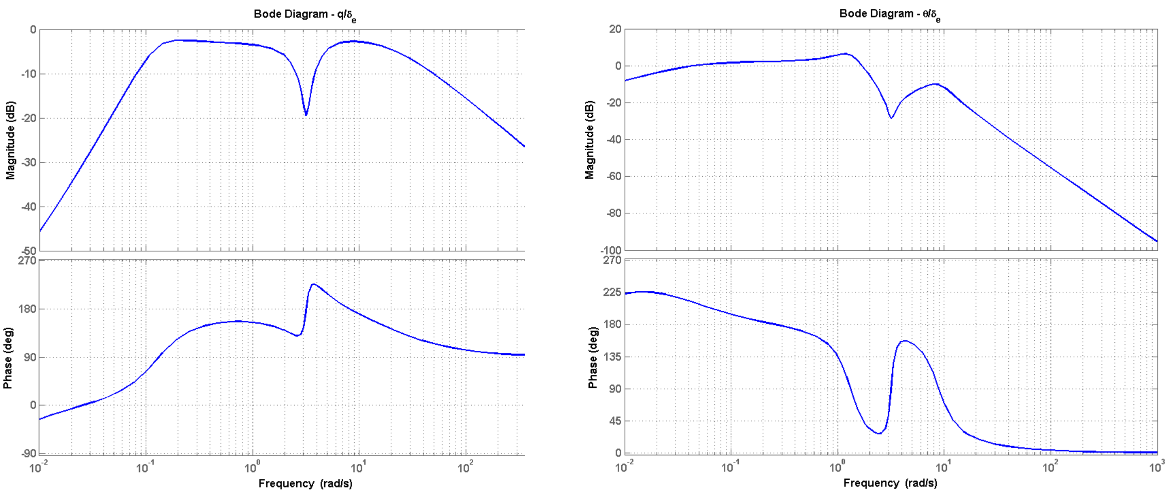
Table 1: Trim points obtained for takeoff rotation

Trim condition	$V_R(m/s)$	θ(deg)	δ_e (deg)	δ_{ih} (deg)
Nose wheel lift-off	80.85	0.73	-6.87	-4.26
On ground roll	80.85	5.73	-10.88	-4.26
In air roll	80.85	8.59	-10.88	-4.26

The results shows that until the rotation begins, the aircraft dynamics is rather stable. From nose wheel lift-off until the end of aircraft rotation the aircraft exhibits both stable and unstable poles. It is important to notice that the stable pair of imaginary poles for the on ground roll have a fast time response of $\tau = 0.38\ s$, what would be equivalent to the short-period poles. As the aircraft has completely lifted-off the ground, it becomes stable again.

From this analysis, the approach used to compute fly-by-wire control laws is straight forward. Given the linear models, requirements are defined based on a desired behavior and the inherit characteristics of the aircraft. It suffices, then, to choose feedback variables and a control law structure. Several authors describes this process as Stevens (2003) and Gangsaas *et al.* (1986). Also, the work developed by Villaumé and Jeanneau (2007) and Villaumé and Duprez (2007) concentrates on examples for on ground control laws.

A classical example is the use of an augmentation stability system in order to improve the takeoff dynamic behavior by changing the frequency and damping of longitudinal modes as well as stabilizing the aircraft during rotation in order to meet handling qualities criteria. This can be accomplished by adopting a feedback control law on the states q or θ. Other requirements may be imposed, in the frequency domain, to the cut-off frequencies and also providing stability margins for gain and phase. Figure 6 shows the open loop bode diagrams of q and θ with respect to an elevator input for the longitudinal frequency response without any stability augmentation system.



(a) Frequency response for open loop $\frac{q}{\delta_e}$ transfer function (b) Frequency response for open loop $\frac{\theta}{\delta_e}$ transfer function

Figure 6: Bode diagram for open loop input to output transfer functions

These control laws are normally set such that the open loop frequency response is shaped in order to achieve a desirable response. The cut-off frequency shall be 50% larger than the short period frequency of the longitudinal mode. As for the stability margins, they are chosen as of $6dB$ for gain and $45\deg$ for phase delay. The rationales for these requirements may be found in the works of Herrera (2014) and Oliveira (2011).

6. CONCLUSIONS

This work presented the main aspects of the development and analysis of an aircraft model suitable for the design of on ground control laws with focus in the takeoff phase. As for the modeling aspects, the main contribution concerns the modeling of ground effort and ground effect phenomena. Unlike other flight phases, these have great influence on the aircraft behavior, as it can be observed by the analysis during the takeoff rotation phase. For a certain period, the aircraft dynamics becomes unstable, what may lead to undesired behavior. Considering the criticality of the takeoff phase, the use of fly-by-wire systems can mitigate these effects and shape the aircraft behavior to patterns determined through design requirements. Following the approach proposed here, the implementation, analysis and computation of these control laws is straight forward. The choice for control variables and design targets are derived directly from stability and control analysis and the frequency response of the open loop linear longitudinal transfer functions.

The study of the aircraft behavior on ground allows for a better understanding of the influence of complex dynamics, such the ones introduced by the landing gears and tires, in the global behavior of the aircraft. This knowledge is crucial for proper fly-by-wire development, driving the definition of consistent requirements and the choice of a proper control law structure and control variables. It is believed that a good control law project relies not only on the techniques used, but also knowing and understanding the main characteristics of the system to be controlled and its limitations. In practice, this makes possible the use of simpler control techniques, reducing engineering effort, development time, costs, and preserving quality and robustness, which are crucial in large scale projects developed in the industry.

Future works would include the development of longitudinal control laws based on the model presented. In a similar way, the same analysis would be applicable to the lateral-directional motion. Important cases of interest are takeoff with one engine inoperative (OEI) and rejected takeoff. The overall process would remain the same, only that now the dynamic modes treated would refer to the lateral-directional ones.

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